ANALYSIS OF COOPERATIVE BEHAVIOR FOR AUTONOMOUS WIDE AREA SEARCH MUNITIONS

THESIS

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Abstract

This research investigates the effectiveness of autonomous wide area search munitions using cooperative and non-cooperative behavior algorithms under various scenarios. The scenarios involve multiple autonomous munitions searching for an unknown number of targets with different priorities at unknown locations. For the cooperative cases, communications are allowed between the munitions to help locate, identify, and decide to pursue an attack on a target or to continue searching the rest of the battlefield. For non cooperative cases, munitions independently search, detect, identify and decide to attack an identified target or continue to search. Performance of the cooperative munitions depends on numerous parameters such as target types, number, mobility, battlefield characteristics, warhead lethality, decision objectives, and variability in the battlefield.

The results were examined under characteristics of warhead lethality, ATR capability, false target attack rate, number of munitions deployed in the simulation, and search weight. Cooperative munitions demonstrated significant decrease in the number of killed targets. Cooperative behavior reduced the number of false target attacks significantly.

ANALYSIS OF COOPERATIVE BEHAVIOR FOR AUTONOMOUS WIDE AREA SEARCH MUNITIONS

I. Introduction

1.1 General

The problem being addressed in this research is the effectiveness of autonomous wide area search munitions using cooperative and non-cooperative behavior algorithms under various scenarios. The scenarios involve multiple autonomous munitions searching for an unknown number of targets with different priorities at unknown locations. For the cooperative cases, communications are allowed between the munitions to help locate, identify, and decide to pursue an attack on a target (and which munition will attack) or to continue searching the rest of the battlefield. For non cooperative cases, munitions independently search, detect, identify and decide whether to attack an identified target or continue to search. Performance of the cooperative munitions depends on numerous parameters such as target types, number, mobility, battlefield characteristics, warhead lethality, decision objectives, and variability in the battlefield.

AFRL/VA sponsored this research. All research was conducted at the Air Force Institute of Technology (AFIT), Wright-Patterson AFB, Ohio.

1.2 Background

Due to the changing national military objectives and diminishing budgets the Air Force has begun to decline the size of its combat forces. For this reason the Air Force is conducting several projects in order to maintain or improve combat effectiveness with fewer numbers. One of the ways of keeping and enhancing its war fighting capabilities is to search for new technical and operational concepts. Mission efficiency has become as important as mission effectiveness, and this has led to interest in small, autonomous cost efficient weapons (1)(2). These autonomous weapons can also be helpful to reduce the mission planning effort and intelligence since they have the ability to search, classify and decide to attack the classified targets.

The smaller the weapons get the harder it is to achieve satisfactory lethality. Some loss in lethality associated with a smaller warhead can be compensated for by more accurate terminal guidance. A complementary approach is to use cooperative behavior to bring multiple munitions to bear on critical targets. The net effect can be to increase both the effectiveness and the efficiency of the overall aircraft/munition system.

A RAND study examined rationale for cooperative behavior between Proliferated Autonomous Weapons (PRAWNS) equipped with near-term automatic target recognition systems (2). Their objective was "to explore the potential of innovative cooperative air-to-ground weapon system concepts that integrate advances in ethology, robotics, and modern military technology". A swarming algorithm was used to implement the desired cooperative behavior. Their study showed that communications, Automatic Target Recognition (ATR) and sensors and navigation system are required to implement the swarming munition concept. Their study showed that by allowing communications between swarm weapons, a group of individually less capable weapons may show capabilities that can exceed those conventional systems with no communication. The decision algorithm used by RAND does not show a comparison of their decision algorithm with other alternatives. Further, the munitions in their study have no possibility of encountering false targets. According to Jacques, false target attacks need to be taken into consideration when evaluating the effectiveness of autonomous wide area search munitions (5). Some false target attacks are inevitable due to the stochastic nature of the ATR process. Therefore, false target attacks must be considered as a degrading parameter for effectiveness in autonomous wide area search munitions.

Gillen investigated cooperative behavior through the use of a simulation program. Gillen developed a decision methodology for cooperative behavior and evaluated the effectiveness of it against a baseline of non-cooperative munitions (3)(4). His study showed that loss of lethality due to a smaller warhead can be overcome by applying cooperative engagement to the wide area search munitions.

In his study, Dunkel showed that cooperative behavior does not always improve the effectiveness of the wide area search munitions (1). The amount of improvement or degradation depends on the form of cooperative behavior and the specific scenario. His study emphasizes that the combination of cooperative classification and attack typically outperforms cooperative attack only because of the lower effective false target attack rate associated with cooperative classification. Park studied the validity of simulations for wide area search munitions (9). His study show that a properly designed wide area search munition simulation can be effectively used to predict the performance of these munitions under prescribed conditions.

1.3 Objectives

The Primary objective of this study is to investigate and compare the effectiveness of wide-area search munitions using cooperative and non cooperative behavior algorithms under various scenarios. More specific sub objectives are:

1. Modify a simulation to highlight possible advantages of cooperative behavior in autonomous wide area search munitions.
2. Further explore under what scenarios it is advantageous or disadvantageous to use cooperative behavior.
3. Compare and find out any benefits gained by implementing cooperative behavior in wide area search munition.
4. Analyze the sensitivities of the decision rules and parameters and determine which parameters should be given special attention.

1. 4 Approach and Scope

For this research a computer simulation is used to model multiple autonomous wide area search munitions that search, classify and attack targets. Within the search area both real and false targets are uniformly distributed. For predetermined battlefield characteristics both non-cooperative and cooperative cases are examined. In the non-cooperative cases autonomous munitions are not allowed to communicate with each other. Hence each individual munition needs to independently search, classify and decide either to attack the classified target or continue to search for new targets.

In the cooperative cases communication between the munitions are allowed. Individual munitions broadcast information regarding classification and attacks to the other agents of the group so every munition can be informed as to the progress of the all munitions. By using this shared information munitions cooperatively classify and decide whether an attack should be made on the target. Cooperative decision logic can also be used to determine which munitions attack classified targets and which continue to search.

Modeling real life, as it is, is beyond the scope of this study. Therefore some simplifying assumptions needed to be made. All communication between munitions is reliable and on time. There is no communication delay, signal degradation or broadcasting errors, but erroneous information regarding incorrectly classified false targets is broadcasted. In this research all targets and non-targets are modeled as stationary. Unreliable, limited communication and mobile targets and non-targets are left as a recommendation for future studies. Various cooperative and non-cooperative scenarios are studied using 4 and 8 munition groups. Parameters used to define the scenarios and battlefield characteristics are shown in the test matrix in Appendix A.

1.5 Relevance

This study does not address any particular autonomous wide area search munition. A generic computer simulation is used to model the problem addressed in this study. Therefore this research and its results and conclusions can be applied any scenario with similar vehicle and battlefield characteristics by simply modifying the simulation parameters. Analytical theory presented in chapter 2 can be applied to a broad range of cooperative search algorithms. This study highlights the crucial decision parameters that should be given special attention when evaluating the effectiveness of the autonomous wide area search munitions under cooperative behavior algorithms.

II. Autonomous Wide Area Search Munitions

2.1 General

Wide area search munitions can be described as autonomous vehicles which have the ability to carry warheads, relatively small onboard sensors to detect and classify targets, navigation systems (INS/GPS) to navigate through the search area, and communication systems to communicate with each other. In this research the munitions carry a single warhead that destroys the munition once detonated; they do not have the ability to drop individual bombs on targets. The Low Cost Autonomous Attack System (LOCAAS) is a very good example of wide area search vehicles that are under development. The LOCAAS is planned to be capable of wide area search, identification and destruction of mobile targets (13).

There are various factors that play a big role in the effectiveness of the wide area search munitions. The most significant factors for overall performance of cooperative munitions are the communication, Automatic Target Recognition (ATR), and warhead lethality. For example, a poor ATR system will cause misclassification of the object and will result in excessive false target attacks and collateral damage. Likewise, bad communication broadcast to other munitions may cause other vehicles to react adversely since decisions will be based on bad information.

According to Jacques (6) False Target Attack Rate (FTAR) and probability of target report (P_{TR}) are the most important measures of ATR performance. FTAR can be defined as the average rate (/km^2) at which munitions would falsely declare targets if the seeker were flown in a non-commit mode. P_{TR} is the probability of a correct Target Report given that a valid target is encountered in the search area. Some classical work in the area of optimal search has been done by Koopman (8) and Washburn (11). In the following sections probabilities for successful search and attack will be examined in detail for single munition/single target, single munition/multi-target, and multi-munition/multi-target cases based on Jacques' studies (5)(7). Prior to defining the probabilities of mission success it is necessary to discuss the ATR algorithm in greater detail.

2.1.1 ATR Algorithm. The performance of an ATR system is determined by its' ability to make the right decision when verifying the type of object (target or non-target) that has been encountered. The process of making the right decision given target encounter is quantified by the probability of target report (P_{TR}). Jacques described the relationship of these probabilities and other ATR measures using a confusion matrix (7). A confusion matrix expresses *a priori* probabilities for discriminating between targets and non targets. A binary confusion matrix is shown in Table 1 for the single target case (1).

Table 1 Binary Confusion Matrix

DECLARED OBJECT	ENCOUNTERED OBJECT	
	Target	Non-Target
Target	P_{TR}	$P_{FTA\|E}$
Non-Target	$1-P_{TR}$	$1-P_{FTA\|E}$

Table 1 shows only a single target type. In addition to P_{TR}, the confusion matrix requires the specification of $P_{FTA|E}$, the probability of false target attack given encounter. This is the simplest case because it contains only a single target type, and any encountered object is either a target or non-target.

In reality it is unrealistic to expect that munitions will encounter only one type of target. For example, there might be surface to air missile launchers, reloaders, and support vehicles in a battlefield scenario. An attack might be considered successful if any of these targets is attacked. Therefore, an ATR model must be capable of handling different types of targets. In order to handle the multiple target type case, an extension of the simple confusion matrix must be considered. The confusion matrix for an ATR capable of discriminating 3 different types of true targets from non-targets is shown in Table 2 (1).

Table 2 Confusion Matrix for Multiple Target Types

DECLARED OBJECT	ENCOUNTERED OBJECT			
	Target Type 1	Target Type 2	Target Type 3	Non-Target
Target Type 1	$P_{TR\ 1\|Type\ 1}$	$P_{TR\ 1\|Type\ 2}$	$P_{TR\ 1\|Type\ 3}$	$P_{FTA1\|E}$
Target Type 2	$P_{TR\ 2\|Type\ 1}$	$P_{TR\ 2\|Type\ 2}$	$P_{TR\ 2\|Type\ 3}$	$P_{FTA2\|E}$
Target Type 3	$P_{TR\ 3\|Type\ 1}$	$P_{TR\ 3\|Type\ 2}$	$P_{TR\ 3\|Type\ 3}$	$P_{FTA3\|E}$
Non-Target	$1-\Sigma P_{TRj\ \|\ Type\ 1}$	$1-\Sigma P_{TRj\ \|\ Type\ 2}$	$1-\Sigma P_{TRj\ \|\ Type\ 3}$	$1-\Sigma P_{FTAj\ \|\ E}$

The composite probability of target report can be determined by using the above confusion matrix for any target type. However, this time it is not a single value since a target encountered by a munition can be classified as any type. For example, if a munition is to encounter a target of Type 1, the probability that it would classify the target as a target of any type is the sum of $P_{TR\ 1|Type\ 1}$, $P_{TR\ 2|Type\ 1}$, $P_{TR\ 3|Type\ 1}$. Note that since any encountered target will either be declared some target type or disregarded as a non-target, the values in any single column must sum to one.

2.2 Single Munition Single Target Case

When a munition searches an area it is only able to see the part of the search area under its sensor footprint, assumed to be constant width in this research. A sample search pattern for the single munition/single target case is shown in Figure 1. For the simplest case, the search area, A_S, contains a single target. For the rest of the chapter targets are considered as uniformly distributed within the search area in a Poisson field of false targets. The basic scenario will be the single munition/single target case. This basic scenario will be extended to a single munition/multi-target case and multi-munition/multi target case.

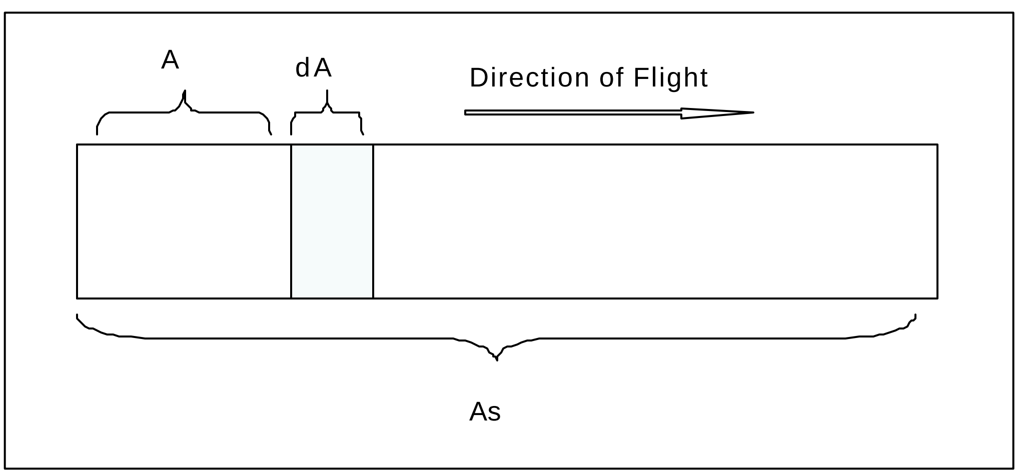

Figure 1 Sample Search Pattern

For the basic scenario, the single munition single target case, a single target is uniformly distributed in a Poisson field of false targets. The probability of mission success for the single munition, single target case can be expressed as:

$$P_{MS} = P_K . P_{TR} . P_E \tag{2.1}$$

where

$P_K =$ the probability of target kill given that the target is classified as a valid target.

P_{TR} = probability of target report given the target is in the sensor footprint.

P_E = the probability the target will be encountered in the search area.

In order to obtain the probability of mission success $P_{K,}$ $P_{TR,}$ and P_E values have to be determined. P_K, can be expressed as single numerical values depending on the warhead lethality, and P_{TR} can be derived from the confusion matrix tables as discussed in section 2.1.1.

The probability that the munition will encounter the target given that the target is in the search area, P_E , can be determined from an integral formulation using the probabilities that the munition has not made previous false target declarations in the already searched area, $P_{\overline{FA}}$, and the probability that the target is contained in the area *dA.*

$$P_{\overline{FA}} = e^{-aA} \tag{2.2}$$

$$P_c(dA) = h_t . dA \tag{2.3}$$

where a is the false target attack rate and the h_t is the average target density for the search area. For the single target case, $h_t = 1/A_S$. As defined in the previous sections false target attack rate is the expected rate of false target declarations for the Sensor/ATR algorithm. It can be formulated as the product of the probability that the munition will attack a false target given that it has been encountered, ($P_{FTA|E}$), and the expected probability density of false targets (h_{FT}).

$$a = h_{FT} \cdot P_{FTA|E} \tag{2.4}$$

Therefore, the incremental probability that the munition will encounter the target in area *dA* can be expressed as:

$$\Delta P_E(A) = \frac{e^{-aA}}{A_s}.dA \tag{2.5}$$

The probability that the munition will encounter the target in the total search area can be obtained by integrating equation 2.5 over the search area A_S yielding:

$$P_E(A_s) = \frac{1 - e^{-aA_s}}{a \cdot A_s} \tag{2.6}$$

2.2.1 Outcome Trees. An outcome tree for the single munition/single target scenario showing the possible outcomes and their likelihoods is shown in Figure 2 (1). Solid lines represent desired outcomes, and dashed lines are the negative outcomes. While a munition is searching the area, it may either encounter the true target or not. If it encounters the true target, because of the uncertainty associated with the ATR process, it may either report it as a true target or a false target. If the real target is recognized by the munition an attack will be executed on the target. Although, there will be an attack on the target it may destroy the target or the target will survive in accordance with the lethality, P_K, of the warhead.

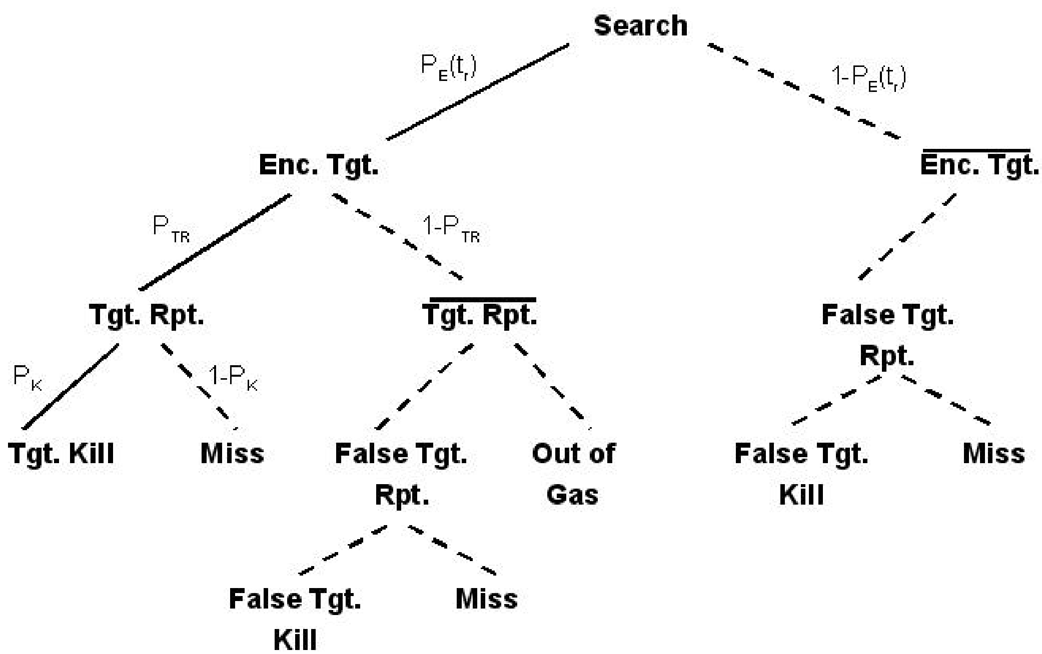

Figure 2 Outcome Tree for Autonomous Search

If the real target is not recognized there is no remaining chance for a successful outcome for the single target case (assuming non-duplicative search pattern). Since there is no real target in the remaining search area the munition will run out of gas and destroy itself or execute an attack on a false target. An alternative outcome is that the munition will make a false target declaration prior to encountering the real target. Consequently, the munition can execute an attack on the false target being recognized as a valid one.

The likelihood of any specific outcome can be determined by simply taking the product of the possibilities along the path of that branch. The probability of successful search is the left branch of the outcome tree. Analytically it can be shown as:

$$P_{SS} = P_K . P_{TR} . P_E = P_{MS} = P_K . P_{TR} . \frac{1-e^{-\alpha A_s}}{\alpha . A_s} \tag{2.7}$$

When a target is reported by the ATR of a different munition it may be a real target or a false target. The probability that a second attack on the declared object will result in a successful target kill can be determined by looking at the outcome tree for the attack Figure 3 (5).

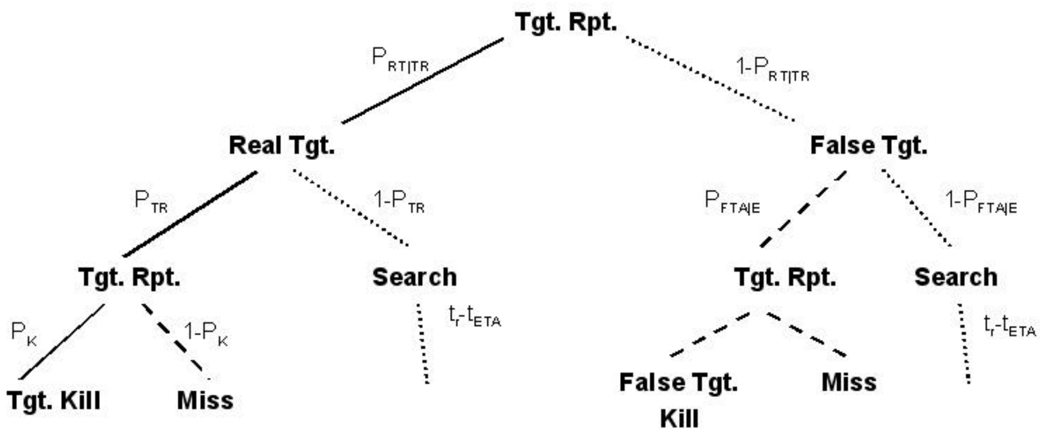

Figure 3 Outcome Tree for Cooperative Attack

The probability of a successful attack, lethal attack on a real target, is the most left branch of the Figure 3.

$$P_{SS} = P_{RT|TR} \,.\, P_{TR} \,.\, P_K \tag{2.8}$$

where $P_{RT|TR}$ is the probability that a declared target is actually a real target given that it is reported. $P_{RT|TR}$ can be expressed as the ratio of the true target attack rate to total attack rate.

$$P_{RT|TR} = \frac{P_{TR} \cdot h_T}{P_{TR} \cdot h_T + P_{FTA|E} \cdot h_{FT}} \tag{2.9}$$

In the search area there is only one target and once it is not recognized by munition's ATR system, the probability of continuing to search for the target will be zero resulting outcomes of all the other branches to be zero as well.

2.3 Single Munition Multi-Target Case

A single munition searching for multiple targets can be looking for multiple targets of the same type, multiple targets of different types or a specific target between a numbers of different valid targets. The ability to distinguish between different target types is again determined by the capability of the munitions' ATR system. When the munition is searching for a specific target among the other types of targets, these other types of targets can simply be considered as false targets and the theory developed for the single munition/single target case can be applied safely.

In the case of a single munition searching for different types of targets, all target types are considered valid. Modifications must be made from the set up of the single munition/single target case to handle this scenario. For the single munition/single target case the incremental probability that the munition will encounter the target in area *dA* was shown to be the product of the probabilities that munition has had no false alarms in the already searched area, $P_{\overline{FA}}$, and the target is contained in the area *dA*. For the multi target scenario there are other valid targets in the search area and the incremental probability of target encounter also depends on the probability of not attacking a target within the already search area. This probability can be expressed as:

$$P_{\overline{RT}} = e^{-h_t P_{TR} A} \qquad (2.10)$$

Thus the incremental probability for target encounter in *dA* is the product of the probability that the munition has had no false alarms in the already searched area, $P_{\overline{FA}}$, the probability that the target is contained in the area *dA*, and the probability of not having a previously declared target within the already search area.

$$\Delta P_E(A) = e^{-(h_t P_{TR} + a)A} \cdot h_t \cdot dA \tag{2.11}$$

Finally 2.11 can be integrated over the entire area to obtain the total probability of target encounter for the entire search area:

$$P_E(A_S) = \frac{h_t}{h_t P_{TR} + a} \cdot (1 - e^{-(h_t P_{TR} + a) A_s}) \tag{2.12}$$

The probability of target report can be determined by using the confusion matrix. However, since a target encountered by the munition can be classified as *any* type, it cannot be taken directly from the confusion matrix as it was for the single target type case. The probability that an encountered target of type *i* will be declared as a target of any type can be defined as:

$$P_{TRi} = \sum_j P_{TRj|Type\_i} \tag{2.13}$$

where j ranges from one to the number of target types being considered in the ATR algorithm. When a munition encounters a target, the probability that this encountered target will be type *i* can be defined as:

$$P_{Ei} = \frac{h_{ti}}{h_{total\_tgts}} \tag{2.14}$$

By using equations 2.13 and 2.14 a combined P_{TR} weighted by the average densities of the various target types can then be stated as:

$$P_{TR} = \sum_i P_{TRi} \cdot P_{Ei} \tag{2.15}$$

2.4 Multi-Munition Multi-Target Case

The analytical studies for the single munition single/target case can still be applicable to the multi munition/multi target cases. Jacques showed the analytical tools for the multi-munition case with single targets and extension of these to the multi-munition/multi-target case (5). For the multi-munition/multi-target case, munitions may still search the area individually, so these searches can be considered independently. Probability of successful search is the same as the single munition/single target case. However, munitions can also execute attacks on targets declared by other munitions.

The probability of successful attack is affected by the other munitions' contribution since individual munitions can execute attacks on the targets declared by another munition. However, its own ATR may or may not recognize it as a target once it is encountered for itself. If not, it may continue to search and can attack successfully another target declared by another munition or find another valid target. By using the outcome tree shown at Figure 3, the probability of a successful attack can be shown as (5):

$$\begin{aligned} P_{sa} = {} & P_K \cdot P_{TR} \cdot P_{RT|TR} + P_{SS}(t_r - t_{ETA}) \cdot (1 - P_{TR}) \cdot P_{RT|TR} + \\ & P_{SS}(t_r - t_{ETA}) \cdot (1 - P_{FTA|FTE}) \cdot (1 - P_{RT|TR}) \end{aligned} \tag{2.16}$$

Different than the single target case, this time there is more than one target in the search area and continuing to search can produce positive outcomes.

2.5 Applying Cooperative Algorithm to This Research

2.5.1 Non-Cooperative Cases. The goal of this research is to evaluate the effectiveness of cooperative behavior in wide area search munitions. In order to accomplish this goal, the performance of cooperative munitions must be compared with the performance of the non-cooperative munitions. Cooperative cases and non-cooperative cases are considered using the same conditions and parameters through various scenarios.

Munitions act individually in non-cooperative cases. A munition searches by itself looking for possible targets. When it encounters an object, it classifies it as either target or non-target by using its ATR system, and when a classification is made it decides whether to execute an attack on the target or continue searching for another target. Munitions will not attack any of the targets that have been classified by any other vehicles unless they are encountered during their individual search. This must be the case since they do not have any knowledge of targets found by other munitions.

2.5.2 Cooperative Cases. In cooperative cases munitions act as a group to accomplish the tasks and maximize the overall benefit for the system. Munitions communicate with each other and they classify the object cooperatively using confirmatory looks. When a classification is made, they decide whether or not an attack should be made on the target, and if an attack is to be made which munition will be assigned to attack.

Benefit calculations will be used to decide which actions to take, and possible tasks are assigned to the vehicles in a way to optimize overall benefit of the group. These possible tasks are confirming the classification of the object, executing an attack on a classified target, or continuing to search for other valid targets. The benefit calculations will be probabilities of success based on the outcomes of search and attack, and their implementation will be discussed in the next chapter.

III. Simulation Program

The MultiUAV simulation used in this research was developed by AFRL/VACA as a development tool for their research on cooperative vehicles. MultiUAV can simulate multiple unmanned air vehicles (UAVs) which can cooperatively act to accomplish a predetermined task (10). MultiUAV was developed using Matlab, Simulink and Microsoft Visual C++ (MSVC++)(12). The MultiUAV simulation obtained from VACA was modified to implement some of the objectives of this research. These modifications and the specifications of the original simulation will be discussed in this chapter. MultiUAV is still under continuous development.

3.1 Original Simulation

3.1.1 General. The original simulation developed by AFRL/VACA was capable of simulating eight vehicles searching an area that contains a maximum of ten targets. Simulated vehicles have embedded flight software (EFS) that can be used to implement cooperative control algorithms and vehicle dynamics. MultiUAV offers tools for plotting the simulation results, and saving data for playback and animation (10).

The number of the vehicles can be changed from 1 to 8 by using a graphical user interface (GUI) provided by the simulation. Increasing the number of vehicles requires complex procedures and is beyond the scope of this research. AFRL has immediate plans to make connections between vehicles in MultiUAV more flexible so that users can add additional vehicles to the simulation (10).

Simulation begins by the random placement of the targets in the search area and the placement of the autonomous vehicles at their initial positions. The vehicles then fly specified routes to search the area for possible targets. When an object enters a vehicle's field of regard it is detected by the sensor of the vehicle and a classification is made as a real target or a non target. A confidence of correct classification for the object is assigned depending on the angle from which the target is viewed by the vehicle. This confidence level has an effect on the task assignment for cooperative munitions because a specified level of confidence must be attained before any attack can occur.

There are certain tasks that a vehicle can perform after classification of the object. These tasks are assigned in a way to maximize the overall benefit (10) (12).

- Continue searching (If the object is classified as a non-target or the calculated benefit of search is greater than the attack benefit)
- Attack (Execute an attack on the object that has been classified as a target)
- Reclassify (If the confidence in target classification is less than the predetermined threshold)
- Verify (Perform Battle Damage Assessment (BDA)).

Vehicles continue to perform these assigned tasks until the total simulation time is expired, at which time the simulation terminates. For this research, a total simulation time of 1200 seconds was used.

3.1.2 Task Assignments. Task assignments are determined by implementing a network optimization model. Currently the simulation uses a Capacitated Transshipment Problem (CTP), a special case of linear programming, to perform the task allocation routine. Tasks are assigned to the munitions in a way that maximizes the overall benefits to the multi-munition system. The capacitated transshipment problem is solved every time when a change occurs in a target state, or when specified time intervals are reached.

As listed in the previous section, possible tasks are to continue searching, attack, reclassify, and verify.

3.1.3 Automatic Target Recognition Algorithm. When a vehicle encounters an object in the original Simulation, it classifies the object based on truth information. It then calculates a confidence level for the classification that has been made depending on the view angle for the object. Vehicles are not allowed to misclassify the objects, thus eliminating any possibility for false target attack. Although we would certainly like to minimize the number of false targets attacks, it is unreasonable to expect that we can entirely eliminate the possibility of occurrence.

Once classified, a calculated confidence level is compared with the predetermined threshold. If the confidence level is less than the threshold another vehicle may be assigned to classify the object depending on the benefit calculation results. Confidence levels for individual vehicles are then combined into a single value and this new metric will be compared to the threshold. The object stays detected but not classified until the confidence becomes greater than the threshold.

It is not possible to have a perfect ATR algorithm. There will be some errors in the ATR system of a real munition and this error should be modeled within the simulation. Modifications to the ATR algorithm of the simulation will be discussed in section 3.2.7.

3.1.4 Warhead Lethality. When a vehicle executes an attack on a target, the target is considered as dead if the bomb drops within a predetermined radius from the target. While this is not an unreasonable approach for large general purpose bombs, the fidelity of the simulation is insufficient to assess the guidance accuracy and the precise pointing required for small warheads. An alternative approach to modeling lethality will be used as described in the next section.

3.1.5 Battle Damage Assessment (BDA). After a target has been attacked, another vehicle may be assigned to perform BDA. Since all attacks result in a kill in the original simulation the vehicle that performs the BDA merely confirms the kill. Having 100% warhead lethality and perfect BDA sensor results in the loss of search time only. There is never any misinformation introduced by the BDA process. This issue also will be discussed in the next section.

3.1.6 Communications. In the original simulation communications are global and reliable. Information is available to all vehicles and there are no errors, loss or bad information broadcasted between the vehicles. Only the truth information is broadcast between vehicles, and vehicles decide cooperatively what to do based on this perfect information. Decisions and task assignments are made based on this truth information.

3.2 Simulation Modifications

In order to adapt the simulation program to the objectives of this research there were several required modifications. The modifications are listed below and will be discussed in more detail in the following subsections.

- Increasing the maximum number of targets
- Adding logic to separate sensed information from truth information
- ATR algorithm modifications
- Adding warhead lethality options
- Benefit and task assignment calculations

- Battle damage assessment
- Obtaining the desired statistical data

3.2.1 Modifying Maximum Number of Targets. For the purposes of this research targets are uniformly distributed in a uniform field of false targets. While the analytical results of the previous section assumed a Poisson field of false targets, this research fixed the number of non-target objects, and uniformly distributed them on the battlefield. In order to employ false targets as well as real targets the maximum number of the targets needed to be increased. The maximum number of targets increased from 10 to 32 to accommodate the desired number of the real targets and false targets. As discussed in the previous chapter, FTAR is the product of the probability that the vehicle will attack an encountered false target and the average density of the non-targets in the search area. The probability of target declaration and attack is determined by the confusion matrix entries, and the non-target density adjusted by adding or removing non-targets.

Distinguishing between the target types and target priorities is also considered an important factor that should be used to evaluate the effectiveness of cooperative behavior. If munitions come across a low priority target and choose to attack in the early stages of the search, they may miss higher probability targets elsewhere in the searchable area. Two types of targets were used in this research; high and low priority targets. Two high priority and four low priority targets are employed along with 26 false targets, resulting $?_{FT}$ = 0.1.

3.2.2 Separation of Truth and Sensed Information. In the original simulation truth information is broadcast between vehicles. Task assignments, classification of targets, benefit calculations and targets states are all based on truth information. As a result, decisions made will also be depending on the same truth information. Although the truth information affects the overall simulation results and effectiveness of cooperative behavior of the vehicles in a positive way, it is not realistic to expect the availability of truth information on the battlefield. Therefore, the favorable results obtained are an overly optimistic prediction.

In real life it is not certain that truth information will be obtained. There are sometimes errors in identification or loss of information. Dunkel (1) made some modifications; as an extension to this work logic was added to the simulation to further distinguish between truth and sensed information. The simulation keeps track of the sensed information generated by the vehicles as well as the truth information. For the purposes of this research, benefit calculations, task assignments and decisions are made according to sensed information. The accuracy of the sensed information broadcast between cooperative munitions will affect the overall results of the simulation much more so than for the case of non-cooperative munitions. For cooperative cases the effect is more detrimental since the bad information will be used by not only the vehicle that created the incorrect information, but also the other vehicles making decisions based on it. This will affect the overall performance of the cooperative behavior algorithms. For the case of no-cooperation these effects may be less significant because bad information will be used only by the vehicle which declared it in the first place.

3.2.3 Automatic Target Recognition Algorithm Modifications. While evaluating the effectiveness of cooperative behavior in wide area search munitions false target attacks due to the misidentification of objects must be considered as a major performance measure (6). False target attacks cause the loss of valuable munitions and result in collateral damage, hence raising political and moral implications. False target attacks are caused by misidentification of a non-target as a real target, and it is very important to account for the possibility of these false classifications in a simulation designated for the evaluation of cooperative vehicle effectiveness.

ATR errors enter into the simulation program through the confusion matrices described in chapter II, and as defined in the simulation. When a vehicle encounters an object, the object will be classified based on the result of a function call which uses true target types, a random number draw and probability entries in the confusion matrix. This final classification is used for benefit calculation and task allocation. By adjusting the probabilities in the confusion matrix different ATR performance levels can be modeled. By letting vehicles misidentify objects the ATR algorithm is more realistic to actual battlefield characteristics.

3.2.4 Warhead Lethality. Modifications were made to implement various low lethality warheads. Fifty percent and eighty percent numbers for warhead lethality are used in both no cooperation and cooperative classification and engagement scenarios. The attack outcome is determined using a random draw and the warhead lethality figure, $P_{K.}$ P_K represents a probability of kill given initiation of attack, and it includes a composite of guidance accuracy, warhead reliability, and lethality given hit on the target.

When a munition executes an attack on a target, a random draw is made and is compared to the P_K value that is hard coded depending on the scenario. If the random number is less than the probability of kill, then the target is considered as killed. However this information is not passed to the other vehicles since the attacking vehicle is already dead. Therefore, the other vehicles only know that an attack has been made on that particular target but they do not have any information regarding the success of attack. A previous attack is used as a degrading factor for the attack benefit calculations and will be discussed in the related subsection.

3.2.5 Battle Damage Assessment. For the scope of this research the BDA task is eliminated by setting the task value of performing BDA to zero.

3.2.6 Benefit and Task Assignment Calculations. The original simulation uses heuristics benefit calculations. In this research a new benefit calculation method proposed by Dunkel is used (1). This approach bases the task benefits on the probabilities of successful attack and search derived in chapter II. A formula for the calculation of search benefit can be expressed as:

$$\textit{Search Benefit} = x \cdot P_{ss} \tag{3.1}$$

where P_{ss} is the probability of successful search and x is a weighting factor. The weighting parameter x is the relative advantage of continuing to search for new targets over executing an attack on an already known target, and can vary between 0 and 1. When x is 0 the search benefit will be zero and it will never be beneficial to search for additional targets. On the other hand, vehicles will always continue to search for additional targets rather than attacking the known ones when x is 1. Dunkel used this weighting function to fine-tune the performance of the cooperative multi-munition system (1).

Various factors affect the task value and probability of a successful attack such as; probability of the target being alive, time needed by the vehicle to reach the target, the probability that the target classification is correct, and different types of targets and target priorities. While the outcomes of previous attacks are known within the simulation, this information is not passed to the other vehicles since the attacking vehicle is already dead. Therefore, the other vehicles only know that an attack has been made on that particular target. One vehicle can execute an attack on a target that has already been attacked by another vehicle, but the probability of a target being alive after *n* previous attack is used as a degrading factor in the benefit calculation. This prevents an excessive number of attacks on already attacked targets. Assuming independent events the probability that a target is still alive after *n* attacks have been made on the target can be expressed as:

$$P_{alive|n\ attacks} = (1 - P_K)^n \tag{3.2}$$

Varying target priorities is also an important factor that should be considered for attack benefit calculations. For this research two types of real targets are assumed to exist on the battlefield. Target Type 1 is considered a high priority target and Target Type 2 is considered a low priority target. A weighting parameter, b is used in benefit calculations to reflect the value of low priority targets relative to that of high priority targets. When b equals 1 low priority targets will be as valuable as high priority targets, and the benefits of attacking either target will be the same. For this research a fixed value of 0.5 is used for the weighting parameter b. Attack benefit formulas can be expressed as:

Target Type 1: $$\textit{Attack Benefit} = (1 - x) \cdot (1 - P_K)^n \cdot P_{sa} \tag{3.3}$$

Target Type 2: $$\textit{Attack Benefit} = (1 - x) \cdot b \cdot (1 - P_K)^n \cdot P_{sa} \tag{3.4}$$

Non-Target (False Target): $$\textit{Attack Benefit} = 0 \tag{3.5}$$

where *(1 - x)* is the weighting parameter associated with attacking a target rather than continuing to search for additional targets. As it can be seen the weighting parameter for attacking a target is the complement of the weighting parameter for search, x. Increasing the value of x, reduces the attack benefits.

3.2.7 Obtaining the Desired Statistical Data and Other Modifications. In order to obtain the desired statistical data some modifications were made. For the purposes of this study, the number of real targets kills, number of false targets kills, number of attacks executed on real and false targets and number of total attacks (including multiple attacks on a target or false target) were gathered. In addition to modifications mentioned in this chapter, there are other modifications made to change the simulation parameters easily without affecting the actual simulation algorithm.

IV. Simulation Results and Analysis

In this research the effectiveness of autonomous wide area search munitions is investigated by applying cooperative and non-cooperative behavior algorithms under various scenarios. These scenarios are defined by several parameters:

1. Warhead lethality
2. ATR performance
3. Search weight
4. Number of munitions and targets
5. False target attack rate (FTAR)

Other parameters such as search rate and search patterns are held constant in this research. While warhead lethality, and ATR capability depend on the munition's technical features, the number of munitions and search weight are determined by the operational concepts and tactics. Two other characteristics related to the search area (battlefield) specifications are the target and false target densities. As discussed in previous chapters these densities are kept constant with six real targets (two Type 1, four Type 2) and 26 false targets in the search area. The specific parameters that are varied in the simulation are shown in Table 3.

Table 3 Specific Simulation Parameters

P_K	Probability of kill	0.5, 0.8
P_{TR}	Probability of target report	0.8, 0.95
FTAR	False target attack rate	0.002, 0.02
N_M	Number of munitions	4, 8
?	Search Weight	0.25, 0.42

The number of attacks made by munitions on real or false targets and the lethality of those attacks are the key elements for mission success and effectiveness, and subsequently the performance of cooperative and non-cooperative wide area search munitions. The specific responses selected are number of killed targets, total number of attacks on false targets, total number of attacks, number of false targets attacked, number of real targets attacked, and the number of attacks executed on high and low priority targets. Finally, a hit formula that assigns 2 points to a priority one target kill, 1 point for a priority two target and -1 point for a false target attack is calculated. The following sections present the performance of cooperative and non-cooperative algorithms for varying values of the munition and scenario parameters.

Cooperative cases and non-cooperative cases are considered under the same conditions and parameters through various scenarios. Munitions act individually in non-cooperative cases. A munition searches by itself looking for possible targets. When it encounters an object, it classifies the target by using ATR system, and when a classification is made it decides whether to execute an attack on the target or continue searching for another target. Non-cooperative munitions will not attack any of the targets that have been classified by any other vehicles unless they are encountered during their individual search. In cooperative cases munitions act as a group to accomplish the tasks and maximize the overall benefit for the system. Munitions communicate with each other and classify the object cooperatively. When a classification is made, they decide whether or not an attack should be made on the target, and if an attack is to be made which munition will be assigned to attack. According to benefit calculations munitions decide which actions to take and possible tasks are assigned to the vehicles in a way to optimize overall benefit of the group. These possible tasks are reclassifying the object, executing an attack on a classified target or continuing to search for other valid targets.

4.1 Warhead Lethality Effects

Warhead lethality is one of the most important factors in determining the performance of the munitions. In this section the performance of cooperative and non-cooperative munitions will be examined by applying low and high warhead lethality into the simulation.

Table 4 shows the performance of cooperative and non-cooperative behavior for a low warhead lethality ($P_K = 0.5$). Except in three of the scenarios, non-cooperative behavior resulted in more real target kills than the cooperative behavior. Cooperative behavior did not improve the number of killed targets; actually there is a decrease in number of kills between 2 to 57 percent through the different scenarios. These results are similar to those of Dunkel (1).

Table 4 Number of Killed Targets/False Target Attacks at Low Warhead Lethality

					No-cooperation		Cooperation		# of Kills	False Target
P_K	FTAR	#Munition	P_{TR}	Weight ξ	# of Kills	# of FTA	# of Kills	# of FTA	Improvement	Attack Decrease
0.5	0.002	4	0.8	0.42	0.5500	0.1000	0.2833	0	-48.5%	-100.0%
				0.25	1.2333	0.2000	0.7333	0	-40.5%	-100.0%
			0.95	0.42	0.6500	0.0667	0.4500	0	-30.8%	-100.0%
				0.25	1.3667	0.1833	1.0833	0	-20.7%	-100.0%
		8	0.8	0.42	0.8667	0.2500	0.4500	0	-48.1%	-100.0%
				0.25	2.2167	0.5333	1.4500	0	-34.6%	-100.0%
			0.95	0.42	0.9500	0.2833	0.6167	0	-35.1%	-100.0%
				0.25	2.5833	0.4333	2.1333	0	-17.4%	-100.0%
	0.02	4	0.8	0.42	0.5000	1.0667	0.2167	0.1667	-56.7%	-84.4%
				0.25	0.8000	1.7667	0.6667	0.2667	-16.7%	-84.9%
			0.95	0.42	0.6333	1.0000	0.2833	0.1500	-55.3%	-85.0%
				0.25	0.9333	1.6500	0.9500	0.2833	1.8%	-82.8%
		8	0.8	0.42	0.8500	2.4000	0.4167	0.3000	-51.0%	-87.5%
				0.25	1.6000	3.5667	1.6667	0.5167	4.2%	-85.5%
			0.95	0.42	0.8667	2.3833	0.5167	0.2167	-40.4%	-90.9%
				0.25	1.8333	3.2500	1.8667	0.6333	1.8%	-80.5%
OVERALL PREFORMANCE					1.152083	1.195833	0.861458333	0.15833333	-25.2%	-86.8%

Cooperative behavior has significantly decreased the number of False Target Attacks (FTA). While non-cooperative munitions attack significant numbers of false targets, the cooperative munitions execute very few attacks on false targets. This is not a surprising result. Since cooperative munitions classify targets cooperatively, the effective false target attack rate is reduced. This also partially explains the decrease in real target attacks; the cooperative behavior effectively reduces the probability of correct target report. There is an 86.8% decrease in the false target attacks as a result of cooperative behavior. This is a promising improvement for wide area search munitions.

Table 5 shows the performance of cooperative and non-cooperative behavior for high warhead lethality ($P_K = 0.8$). Non-cooperative munitions again kill more real targets than the cooperative munitions for all given scenarios. The decrease in number of killed targets varies between 15 to 48 percent throughout the different scenarios. Overall, the decrease in the number of killed targets for high warhead lethality cases is 29.3%. Cooperative behavior was less beneficial in high warhead lethality cases than it was for low lethality cases. This is because there is less need for multiple attacks on a real target in order to achieve a target kill. High warhead lethality reduces the benefit of executing additional attacks on previously attacked targets. Recall the factor $(1-P_K)^n$ from previous chapters. As a result, munitions prefer to attack targets that have not previously been attacked as they would under non-cooperative conditions.

While the decrease in real target kills is regrettable, it may be an acceptable trade for some scenarios given the significant reduction in false target attacks and collateral damage. Of interest is that the combination of low P_K and higher FTAR are the scenarios where cooperative behavior is most beneficial. Further, this scenario is the most likely for a small, low cost-munition.

Table 5 Number of Killed Targets/False Target Attacks at High Warhead Lethality

					No-cooperation		Cooperation		# of Kills	False Target
P_K	FTAR	#Munition	P_{TR}	Weight ξ	# of Kills	# of FTA	# of Kills	# of FTA	Improvement	Attack Decrease
0.8	0.002	4	0.8	0.42	0.8167	0.1000	0.4333	0	-46.9%	-100.0%
				0.25	2.0167	0.2167	1.1833	0	-41.3%	-100.0%
			0.95	0.42	1.0333	0.0667	0.6500	0	-37.1%	-100.0%
				0.25	2.2833	0.2000	1.6167	0	-29.2%	-100.0%
		8	0.8	0.42	1.2333	0.2500	0.7167	0	-41.9%	-100.0%
				0.25	3.1667	0.4333	2.2500	0	-28.9%	-100.0%
			0.95	0.42	1.4333	0.2833	0.9667	0	-32.6%	-100.0%
				0.25	3.8833	0.3667	3.0333	0	-21.9%	-100.0%
	0.02	4	0.8	0.42	0.7167	1.0667	0.3667	0.1667	-48.8%	-84.4%
				0.25	1.4667	1.8167	1.0500	0.2667	-28.4%	-85.3%
			0.95	0.42	0.9167	1.0000	0.4833	0.1500	-47.3%	-85.0%
				0.25	1.7000	1.6833	1.4500	0.2333	-14.7%	-86.1%
		8	0.8	0.42	1.1667	2.4000	0.6833	0.3000	-41.4%	-87.5%
				0.25	2.7667	3.5667	2.2000	0.5667	-20.5%	-84.1%
			0.95	0.42	1.3000	2.3833	0.8833	0.2167	-32.1%	-90.9%
				0.25	3.0833	3.1833	2.5333	0.4667	-17.8%	-85.3%
OVERALL PREFORMANCE					1.811458	1.188542	1.28125	0.14791667	-29.3%	-87.6%

4.2 ATR Capability Effects

The automatic target recognition system is used by munitions to identify the object they encounter while searching the battlefield for valid targets. The ability of a munition to correctly identify the objects is defined by the probability of target report (P_{TR}), as described in chapter II. In this section the effects of P_{TR} on the performance of the cooperative and non-cooperative munitions will be discussed.

The performance of cooperative and non-cooperative behavior for low ATR capability ($P_{TR} = 0.8$) is shown in Table 6, and high ATR capability ($P_{TR} = 0.95$) is shown in Table 7.

Table 6 Number of Killed Targets/False Target Attacks at Low ATR Capability

					No-cooperation		Cooperation		# of Kills	False Target
P_{TR}	P_K	FTAR	#Munition	Weight ξ	# of Kills	# of FTA	# of Kills	# of FTA	Improvement	Attack Decrease
0.8	0.5	0.002	4	0.42	0.5500	0.1000	0.2833	0	-48.5%	-100.0%
				0.25	1.2333	0.2000	0.7333	0	-40.5%	-100.0%
			8	0.42	0.8667	0.2500	0.4500	0	-48.1%	-100.0%
				0.25	2.2167	0.5333	1.4500	0	-34.6%	-100.0%
		0.02	4	0.42	0.8167	0.1000	0.4333	0	-46.9%	-100.0%
				0.25	2.0167	0.2167	1.1833	0	-41.3%	-100.0%
			8	0.42	1.2333	0.2500	0.7167	0	-41.9%	-100.0%
				0.25	3.1667	0.4333	2.2500	0	-28.9%	-100.0%
	0.8	0.002	4	0.42	0.5000	1.0667	0.2167	0.1667	-56.7%	-84.4%
				0.25	0.8000	1.7667	0.6667	0.2667	-16.7%	-84.9%
			8	0.42	0.8500	2.4000	0.4167	0.3000	-51.0%	-87.5%
				0.25	1.6000	3.5667	1.6667	0.5167	4.2%	-85.5%
		0.02	4	0.42	0.7167	1.0667	0.3667	0.1667	-48.8%	-84.4%
				0.25	1.4667	1.8167	1.0500	0.2667	-28.4%	-85.3%
			8	0.42	1.1667	2.4000	0.6833	0.3000	-41.4%	-87.5%
				0.25	2.7667	3.5667	2.2000	0.5667	-20.5%	-84.1%
OVERALL PREFORMANCE					1.372917	1.233333	0.922916667	0.159375	-32.8%	-87.1%

Table 7 Number of Killed Targets/False Target Attacks at High ATR Capability

					No-cooperation		Cooperation		# of Kills	False Target
P_{TR}	P_K	FTAR	#Munition	Weight ξ	# of Kills	# of FTA	# of Kills	# of FTA	Improvement	Attack Decrease
0.95	0.5	0.002	4	0.42	0.6500	0.0667	0.4500	0	-30.8%	-100.0%
				0.25	1.3667	0.1833	1.0833	0	-20.7%	-100.0%
			8	0.42	0.9500	0.2833	0.6167	0	-35.1%	-100.0%
				0.25	2.5833	0.4333	2.1333	0	-17.4%	-100.0%
		0.02	4	0.42	1.0333	0.0667	0.6500	0	-37.1%	-100.0%
				0.25	2.2833	0.2000	1.6167	0	-29.2%	-100.0%
			8	0.42	1.4333	0.2833	0.9667	0	-32.6%	-100.0%
				0.25	3.8833	0.3667	3.0333	0	-21.9%	-100.0%
	0.8	0.002	4	0.42	0.6333	1.0000	0.2833	0.1500	-55.3%	-85.0%
				0.25	0.9333	1.6500	0.9500	0.2833	1.8%	-82.8%
			8	0.42	0.8667	2.3833	0.5167	0.2167	-40.4%	-90.9%
				0.25	1.8333	3.2500	1.8667	0.6333	1.8%	-80.5%
		0.02	4	0.42	0.9167	1.0000	0.4833	0.1500	-47.3%	-85.0%
				0.25	1.7000	1.6833	1.4500	0.2333	-14.7%	-86.1%
			8	0.42	1.3000	2.3833	0.8833	0.2167	-32.1%	-90.9%
				0.25	3.0833	3.1833	2.5333	0.4667	-17.8%	-85.3%
OVERALL PREFORMANCE					1.590625	1.151042	1.219791667	0.146875	-23.3%	-87.2%

The high ATR capability scenarios for both non-cooperative and cooperative munitions achieved better results as compared to the low ATR capability cases. ATR systems with high P_{TR} produce more certain classification of the objects leading to a reduction in missed targets. Of note, cooperative behavior was more beneficial for cases of high P_{TR} than it was for low P_{TR}. While the average false target attack decrease was not sufficiently different for the two cases, (87.2% vs. 87.1%), the decrease in real target attacks was significantly less for the high P_{TR} case (-23.3%) than it was for the low P_{TR} case (32.8%).

4.3 Effects of Number of Munitions

The performance of cooperative and non-cooperative behavior for 4 and 8 munitions is examined in this section. Simulation results for 4 munition scenarios are shown in Table 8, and the 8 munition results are shown in Table 9. It is seen that there is 32.5% percent decrease in number of targets killed and 86.2% less false targets attacks for 4 munitions scenarios and 24.9% percent decrease in number of targets and 87.6% less false targets attacks for 8 munitions scenarios.

Table 8 Number of Killed Targets/False Target Attacks for 4 Munitions

					No-cooperation		Cooperation		# of Kills	False Target
#Munition	FTAR	P_K	P_{TR}	Weight ξ	# of Kills	# of FTA	# of Kills	# of FTA	Improvement	Attack Decrease
4	0.002	0.5	0.8	0.42	0.5500	0.1000	0.283333	0	-48.5%	-100.0%
				0.25	1.2333	0.2000	0.733333	0	-40.5%	-100.0%
			0.95	0.42	0.6500	0.0667	0.45	0	-30.8%	-100.0%
				0.25	1.3667	0.1833	1.083333	0	-20.7%	-100.0%
		0.8	0.8	0.42	0.8167	0.1000	0.433333	0	-46.9%	-100.0%
				0.25	2.0167	0.2167	1.183333	0	-41.3%	-100.0%
			0.95	0.42	1.0333	0.0667	0.65	0	-37.1%	-100.0%
				0.25	2.2833	0.2000	1.616667	0	-29.2%	-100.0%
	0.02	0.5	0.8	0.42	0.5000	1.0667	0.216667	0.166667	-56.7%	-84.4%
				0.25	0.8000	1.7667	0.666667	0.266667	-16.7%	-84.9%
			0.95	0.42	0.6333	1.0000	0.283333	0.15	-55.3%	-85.0%
				0.25	0.9333	1.6500	0.95	0.283333	1.8%	-82.8%
		0.8	0.8	0.42	0.7167	1.0667	0.366667	0.166667	-48.8%	-84.4%
				0.25	1.4667	1.8167	1.05	0.266667	-28.4%	-85.3%
			0.95	0.42	0.9167	1.0000	0.483333	0.15	-47.3%	-85.0%
				0.25	1.7000	1.6833	1.45	0.233333	-14.7%	-86.1%
OVERALL PREFORMANCE					1.101042	0.761458	0.74375	0.105208	-32.5%	-86.2%

Table 9 Number of Killed Targets/False Target Attacks for 8 Munitions

					No-cooperation		Cooperation		# of Kills	False Target
#Munition	FTAR	P_K	P_{TR}	Weight ξ	# of Kills	# of FTA	# of Kills	# of FTA	Improvement	Attack Decrease
8	0.002	0.5	0.8	0.42	0.8667	0.2500	0.4500	0	-48.1%	-100.0%
				0.25	2.2167	0.5333	1.4500	0	-34.6%	-100.0%
			0.95	0.42	0.9500	0.2833	0.6167	0	-35.1%	-100.0%
				0.25	2.5833	0.4333	2.1333	0	-17.4%	-100.0%
		0.8	0.8	0.42	1.2333	0.2500	0.7167	0	-41.9%	-100.0%
				0.25	3.1667	0.4333	2.2500	0	-28.9%	-100.0%
			0.95	0.42	1.4333	0.2833	0.9667	0	-32.6%	-100.0%
				0.25	3.8833	0.3667	3.0333	0	-21.9%	-100.0%
	0.02	0.5	0.8	0.42	0.8500	2.4000	0.4167	0.3000	-51.0%	-87.5%
				0.25	1.6000	3.5667	1.6667	0.5167	4.2%	-85.5%
			0.95	0.42	0.8667	2.3833	0.5167	0.2167	-40.4%	-90.9%
				0.25	1.8333	3.2500	1.8667	0.6333	1.8%	-80.5%
		0.8	0.8	0.42	1.1667	2.4000	0.6833	0.3000	-41.4%	-87.5%
				0.25	2.7667	3.5667	2.2000	0.5667	-20.5%	-84.1%
			0.95	0.42	1.3000	2.3833	0.8833	0.2167	-32.1%	-90.9%
				0.25	3.0833	3.1833	2.5333	0.4667	-17.8%	-85.3%
OVERALL PREFORMANCE					1.8625	1.622917	1.398958	0.201042	-24.9%	-87.6%

The ratio of killed targets to the number of munitions represents the effectiveness of the munitions. For non-cooperative 4 munition and 8 munition scenarios, the effectiveness is 27.5% and 23.2% respectively. And for cooperative 4 and 8 munition scenarios the effectiveness of the munition is 18.5% and 17.4% respectively. The effectiveness of munitions for both cooperative and non-cooperative 8 munitions scenarios is lower than the 4 munition scenarios. Note, however, that there is less of a reduction in effectiveness due to the cooperation when greater numbers of munitions are available.

4.4 Search Weight Effects

Table 10 shows the performance of cooperative and non- cooperative behavior when they operate under low search weight, and Table 11 shows similar results for the cases where a high search weight was used. It is seen that search weight has a very important effect on the number of attacks for both cooperative and non-cooperative munition performance. Recall that search weight is the relative benefit of continuing to search for additional new valid targets compared to attacking already known targets.

Table 10 Number of Killed Targets/False Target Attacks at Low Search Weight

					No-cooperation		Cooperation		# of Kills	False Target
Weight ξ	P_K	FTAR	#Munition	P_{TR}	# of Kills	# of FTA	# of Kills	# of FTA	Improvement	Attack Decrease
0.25	0.5	0.002	4	0.8	1.2333	0.2000	0.7333	0.0000	-40.5%	-100.0%
				0.95	1.3667	0.1833	1.0833	0.0000	-20.7%	-100.0%
			8	0.8	2.2167	0.5333	1.4500	0.0000	-34.6%	-100.0%
				0.95	2.5833	0.4333	2.1333	0.0000	-17.4%	-100.0%
		0.02	4	0.8	2.0167	0.2167	1.1833	0.0000	-41.3%	-100.0%
				0.95	2.2833	0.2000	1.6167	0.0000	-29.2%	-100.0%
			8	0.8	3.1667	0.4333	2.2500	0.0000	-28.9%	-100.0%
				0.95	3.8833	0.3667	3.0333	0.0000	-21.9%	-100.0%
	0.8	0.002	4	0.8	0.8000	1.7667	0.6667	0.2667	-16.7%	-84.9%
				0.95	0.9333	1.6500	0.9500	0.2833	1.8%	-82.8%
			8	0.8	1.6000	3.5667	1.6667	0.5167	4.2%	-85.5%
				0.95	1.8333	3.2500	1.8667	0.6333	1.8%	-80.5%
		0.02	4	0.8	1.4667	1.8167	1.0500	0.2667	-28.4%	-85.3%
				0.95	1.7000	1.6833	1.4500	0.2333	-14.7%	-86.1%
			8	0.8	2.7667	3.5667	2.2000	0.5667	-20.5%	-84.1%
				0.95	3.0833	3.1833	2.5333	0.4667	-17.8%	-85.3%
OVERALL PREFORMANCE					2.0583	1.4406	1.6167	0.2021	-21.5%	-86.0%

Table 11 Number of Killed Targets/False Target Attacks at High Search Weight

					No-cooperation		Cooperation		# of Kills	False Target
Weight ξ	P_K	FTAR	#Munition	P_{TR}	# of Kills	# of FTA	# of Kills	# of FTA	Improvement	Attack Decrease
0.42	0.5	0.002	4	0.8	0.5500	0.1000	0.2833	0.0000	-48.5%	-100.0%
				0.95	0.6500	0.0667	0.4500	0.0000	-30.8%	-100.0%
			8	0.8	0.8667	0.2500	0.4500	0.0000	-48.1%	-100.0%
				0.95	0.9500	0.2833	0.6167	0.0000	-35.1%	-100.0%
		0.02	4	0.8	0.8167	0.1000	0.4333	0.0000	-46.9%	-100.0%
				0.95	1.0333	0.0667	0.6500	0.0000	-37.1%	-100.0%
			8	0.8	1.2333	0.2500	0.7167	0.0000	-41.9%	-100.0%
				0.95	1.4333	0.2833	0.9667	0.0000	-32.6%	-100.0%
	0.8	0.002	4	0.8	0.5000	1.0667	0.2167	0.1667	-56.7%	-84.4%
				0.95	0.6333	1.0000	0.2833	0.1500	-55.3%	-85.0%
			8	0.8	0.8500	2.4000	0.4167	0.3000	-51.0%	-87.5%
				0.95	0.8667	2.3833	0.5167	0.2167	-40.4%	-90.9%
		0.02	4	0.8	0.7167	1.0667	0.3667	0.1667	-48.8%	-84.4%
				0.95	0.9167	1.0000	0.4833	0.1500	-47.3%	-85.0%
			8	0.8	1.1667	2.4000	0.6833	0.3000	-41.4%	-87.5%
				0.95	1.3000	2.3833	0.8833	0.2167	-32.1%	-90.9%
OVERALL PREFORMANCE					0.9052	0.9438	0.5260	0.1042	-41.9%	-89.0%

At low search weight both no cooperation and cooperation execute more attacks on targets than they do for high search weights. It is seen that high search weight has decreased the number of killed targets drastically. This is due to the fact that munitions prefer to continue to search for additional targets instead of attacking the already known ones. Although a value of 0.5 would set the search and attack benefits equal to their calculated probabilities of success; however, this research, as in previous research by Dunkel (1), demonstrated the need to adjust the weights accordingly.

4.5 False Target Attack Rate Effects

As discussed in previous chapters false target attack rate (FTAR) is a very important measure for evaluating the effectiveness of wide area search munitions. The next two tables show the effects of FTAR on the performance of cooperative and non-cooperative munitions.

Table 12 shows the performance of cooperative and non-cooperative behavior at low FTAR values and Table 13 shows the comparative performance for a higher FTAR value. As it can be seen from the table non-cooperative behavior killed more targets than the cooperative behavior. On the other hand cooperative behavior executes very few false target attacks. This is a very important consideration for cooperative algorithms.

Table 12 Number of Killed Targets/False Target Attacks at Low FTAR

					No-cooperation		Cooperation		# of Kills	False Target
FTAR	P_K	#Munition	P_{TR}	Weight ξ	# of Kills	# of FTA	# of Kills	# of FTA	Improvement	Attack Decrease
0.002	0.5	4	0.8	0.42	0.5500	0.1000	0.2833	0.0000	-48.5%	-100.0%
				0.25	1.2333	0.2000	0.7333	0.0000	-40.5%	-100.0%
			0.95	0.42	0.6500	0.0667	0.4500	0.0000	-30.8%	-100.0%
				0.25	1.3667	0.1833	1.0833	0.0000	-20.7%	-100.0%
		8	0.8	0.42	0.8667	0.2500	0.4500	0.0000	-48.1%	-100.0%
				0.25	2.2167	0.5333	1.4500	0.0000	-34.6%	-100.0%
			0.95	0.42	0.9500	0.2833	0.6167	0.0000	-35.1%	-100.0%
				0.25	2.5833	0.4333	2.1333	0.0000	-17.4%	-100.0%
	0.8	4	0.8	0.42	0.8167	0.1000	0.4333	0.0000	-46.9%	-100.0%
				0.25	2.0167	0.2167	1.1833	0.0000	-41.3%	-100.0%
			0.95	0.42	1.0333	0.0667	0.6500	0.0000	-37.1%	-100.0%
				0.25	2.2833	0.2000	1.6167	0.0000	-29.2%	-100.0%
		8	0.8	0.42	1.2333	0.2500	0.7167	0.0000	-41.9%	-100.0%
				0.25	3.1667	0.4333	2.2500	0.0000	-28.9%	-100.0%
			0.95	0.42	1.4333	0.2833	0.9667	0.0000	-32.6%	-100.0%
				0.25	3.8833	0.3667	3.0333	0.0000	-21.9%	-100.0%
OVERALL PREFORMANCE					1.6427	0.2479	1.1281	0.0000	-31.3%	-100.0%

This may indicate that for moderate to high FTAR rate cooperative behavior can improve the overall performance by reducing the number of false target attacks, leaving more munitions available to find and attack real targets.

Table 13 Number of Killed Targets/False Target Attacks at High FTAR

					No-cooperation		Cooperation		# of Kills	False Target
FTAR	P_K	#Munition	P_{TR}	Weight ξ	# of Kills	# of FTA	# of Kills	# of FTA	Improvement	Attack Decrease
0.02	0.5	4	0.8	0.42	0.5000	1.0667	0.2167	0.1667	-56.7%	-84.4%
				0.25	0.8000	1.7667	0.6667	0.2667	-16.7%	-84.9%
			0.95	0.42	0.6333	1.0000	0.2833	0.1500	-55.3%	-85.0%
				0.25	0.9333	1.6500	0.9500	0.2833	1.8%	-82.8%
		8	0.8	0.42	0.8500	2.4000	0.4167	0.3000	-51.0%	-87.5%
				0.25	1.6000	3.5667	1.6667	0.5167	4.2%	-85.5%
			0.95	0.42	0.8667	2.3833	0.5167	0.2167	-40.4%	-90.9%
				0.25	1.8333	3.2500	1.8667	0.6333	1.8%	-80.5%
	0.8	4	0.8	0.42	0.7167	1.0667	0.3667	0.1667	-48.8%	-84.4%
				0.25	1.4667	1.8167	1.0500	0.2667	-28.4%	-85.3%
			0.95	0.42	0.9167	1.0000	0.4833	0.1500	-47.3%	-85.0%
				0.25	1.7000	1.6833	1.4500	0.2333	-14.7%	-86.1%
		8	0.8	0.42	1.1667	2.4000	0.6833	0.3000	-41.4%	-87.5%
				0.25	2.7667	3.5667	2.2000	0.5667	-20.5%	-84.1%
			0.95	0.42	1.3000	2.3833	0.8833	0.2167	-32.1%	-90.9%
				0.25	3.0833	3.1833	2.5333	0.4667	-17.8%	-85.3%
OVERALL PREFORMANCE					1.3208	2.1365	1.0146	0.3063	-23.2%	-85.7%

4.6 Overall results.

As discussed in previous sections non-cooperative munitions perform better than the cooperative munitions in terms of number of killed targets, and cooperative munitions reduced the number of false target attacks to near zero! Table 14 shows the overall results of all scenarios for number of killed targets and number of attacks executed on the false targets. Non-cooperative munitions executed more attacks on both real targets and false targets, resulting in more killed targets and false targets attacks and kills. Cooperative behavior in wide area search munitions did not improve the number of targets killed, but decreased the number of false targets attacks significantly compared to non-cooperative behavior. Cooperative behavior decreased the number of killed targets by 27.7% and also decreased the false target attacks by 87.2%. The decrease in false target attacks is a promising improvement for cooperative behavior algorithms in wide area search munitions.

Table 14 Number of Killed Targets/False Target Attacks for Overall Simulation Results

					No-cooperation		Cooperation		# of Kills	False Target
P_K	FTAR	#Munition	P_{TR}	Weight ξ	# of Kills	# of FTA	# of Kills	# of FTA	Improvement	Attack Decrease
0.5	0.002	4	0.8	0.42	0.5500	0.1000	0.2833	0	-48.5%	-100.0%
				0.25	1.2333	0.2000	0.7333	0	-40.5%	-100.0%
			0.95	0.42	0.6500	0.0667	0.4500	0	-30.8%	-100.0%
				0.25	1.3667	0.1833	1.0833	0	-20.7%	-100.0%
		8	0.8	0.42	0.8667	0.2500	0.4500	0	-48.1%	-100.0%
				0.25	2.2167	0.5333	1.4500	0	-34.6%	-100.0%
			0.95	0.42	0.9500	0.2833	0.6167	0	-35.1%	-100.0%
				0.25	2.5833	0.4333	2.1333	0	-17.4%	-100.0%
	0.02	4	0.8	0.42	0.5000	1.0667	0.2167	0.1667	-56.7%	-84.4%
				0.25	0.8000	1.7667	0.6667	0.2667	-16.7%	-84.9%
			0.95	0.42	0.6333	1.0000	0.2833	0.1500	-55.3%	-85.0%
				0.25	0.9333	1.6500	0.9500	0.2833	1.8%	-82.8%
		8	0.8	0.42	0.8500	2.4000	0.4167	0.3000	-51.0%	-87.5%
				0.25	1.6000	3.5667	1.6667	0.5167	4.2%	-85.5%
			0.95	0.42	0.8667	2.3833	0.5167	0.2167	-40.4%	-90.9%
				0.25	1.8333	3.2500	1.8667	0.6333	1.8%	-80.5%
0.8	0.002	4	0.8	0.42	0.8167	0.1000	0.4333	0	-46.9%	-100.0%
				0.25	2.0167	0.2167	1.1833	0	-41.3%	-100.0%
			0.95	0.42	1.0333	0.0667	0.6500	0	-37.1%	-100.0%
				0.25	2.2833	0.2000	1.6167	0	-29.2%	-100.0%
		8	0.8	0.42	1.2333	0.2500	0.7167	0	-41.9%	-100.0%
				0.25	3.1667	0.4333	2.2500	0	-28.9%	-100.0%
			0.95	0.42	1.4333	0.2833	0.9667	0	-32.6%	-100.0%
				0.25	3.8833	0.3667	3.0333	0	-21.9%	-100.0%
	0.02	4	0.8	0.42	0.7167	1.0667	0.3667	0.1667	-48.8%	-84.4%
				0.25	1.4667	1.8167	1.0500	0.2667	-28.4%	-85.3%
			0.95	0.42	0.9167	1.0000	0.4833	0.1500	-47.3%	-85.0%
				0.25	1.7000	1.6833	1.4500	0.2333	-14.7%	-86.1%
		8	0.8	0.42	1.1667	2.4000	0.6833	0.3000	-41.4%	-87.5%
				0.25	2.7667	3.5667	2.2000	0.5667	-20.5%	-84.1%
			0.95	0.42	1.3000	2.3833	0.8833	0.2167	-32.1%	-90.9%
				0.25	3.0833	3.1833	2.5333	0.4667	-17.8%	-85.3%
OVERALL PREFORMANCE					1.481771	1.192188	1.071354167	0.153125	-27.7%	-87.2%

In order to make a reasonable trade off and take advantage of cooperative behavior in munitions systems, it is very important to understand the performance of cooperative behavior under varying scenarios. Although cooperative munitions performed worse than the non-cooperative munitions for in terms of target kills, for low warhead lethality, high

P_{TR}, greater number of munitions and higher FTAR scenarios cooperative behavior achieved significant reductions in the number of false target attacks, at the expense of a relatively small decrease in number of killed targets.

FTAR and probability of target report are competing objects. For a given sensor and ATR system, lower FTAR and higher P_{TR} cannot be achieved simultaneously. One must make some trade off between these competing objects. Keeping FTAR too low leads to a higher rate of missed targets. Likewise, having P_{TR} too high makes the ATR system very sensitive, resulting in a higher FTAR due to the misidentification of non-targets targets as. One possibility for a trade off between these objectives is to adjust the ATR to keep P_{TR} high, and apply cooperative behavior to achieve a lower false target attack rate. This is a relatively easy and cost effective way to get the desired ATR performance without incurring the size and cost of a more sophisticated ATR system. Further, combining this approach with small low cost warheads (low P_K) potentially leads to a small, low-cost system that can be employed in greater numbers. The platform that launches these wide area search munitions, a fighter aircraft, cargo or even a UAV, will have the ability to carry more munitions to achieve mission success. The increase in the number of munitions will also increase the reliability of the overall munition system. Hence, an effective munition system can be achieved cost efficiently.

4.7 Number of Attacks

In this section the performance of cooperative and non-cooperative munitions will be examined for number of false target attacks and real target attacks. Non-cooperative munitions executed more attacks on both real and false targets than the cooperative munitions. In order to understand the effectiveness and value of the attacks, the number of attacks executed on individual targets and the total number of attacks made by munitions will be compared.

4.7.1 False target attacks. Figure 4 shows the number of false targets (#AttackedFalseTgt) attacked and the total number of attacks (#AttacksFalseTgts) made on false targets by cooperative munitions. As can be seen from Figure 4, for low FTAR cooperative munitions have zero attacks on false targets. With low search weight and low warhead lethality scenarios ($P_K = 0.5$), cooperative munitions execute more attacks on previously attacked false targets. Once a false target is falsely classified as a valid target, munitions treat it as a real target and calculate task benefits as if it is a real target. This is due to the fact that benefit calculations for low warhead lethality give a higher probability that the attacked target is still alive than in the high warhead lethality scenarios. In addition, a low search weight results in munitions attacking known targets rather than looking for additional targets. As a result, cooperative munitions execute multiple attacks on targets that have been attacked previously but likely still alive. For all other scenarios munitions rarely attack an already attacked false target.

The number of false targets that have been attacked and the total number of attacks made on false targets by non-cooperative munitions is shown Figure 5. Non-cooperative munitions attack known targets at a smaller ratio for low warhead lethality and low search weight. This is as expected since non-cooperative munitions have no communication and therefore have no knowledge of previous attacks.

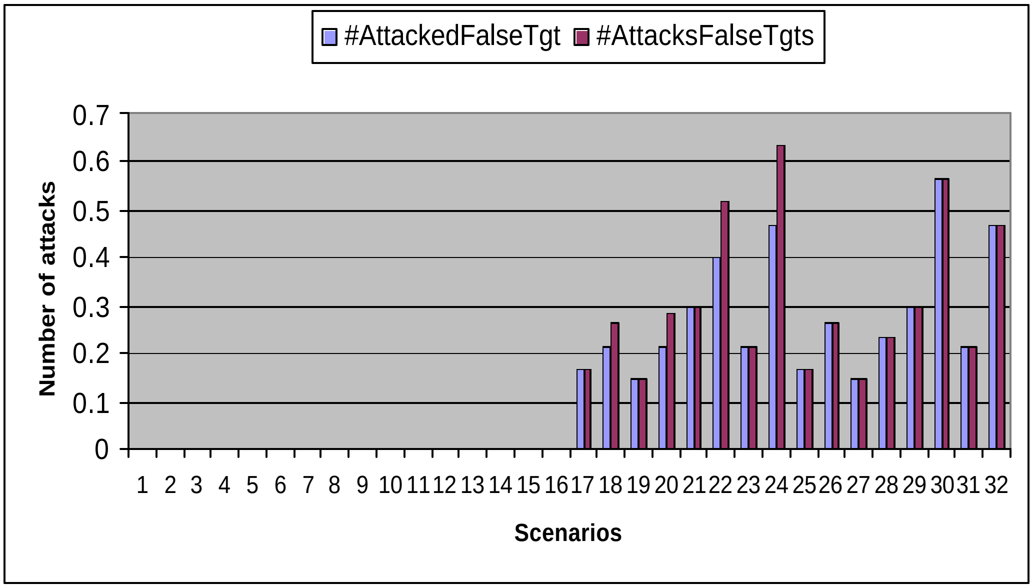

Figure 4 Number of False Target Attacks for Cooperative Munitions

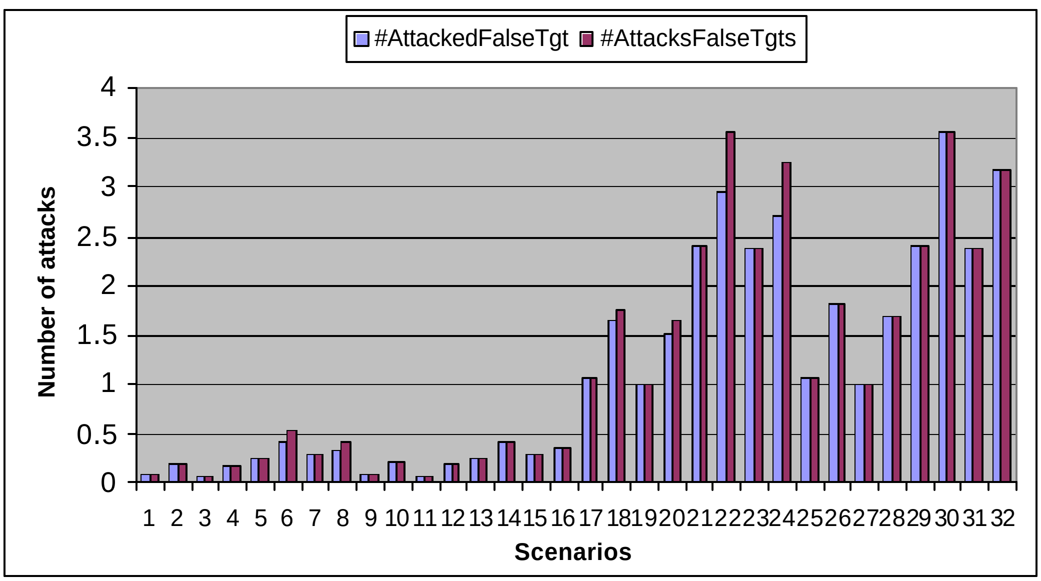

Figure 5 Number of False Target Attacks for Non-cooperative Munitions

4.7.2 Real Target Attacks. Figure 6 shows the number of real targets (#AttackedTargets) that have been attacked and the total number of attacks (#AttacksTargets) made on real targets by cooperative munitions.

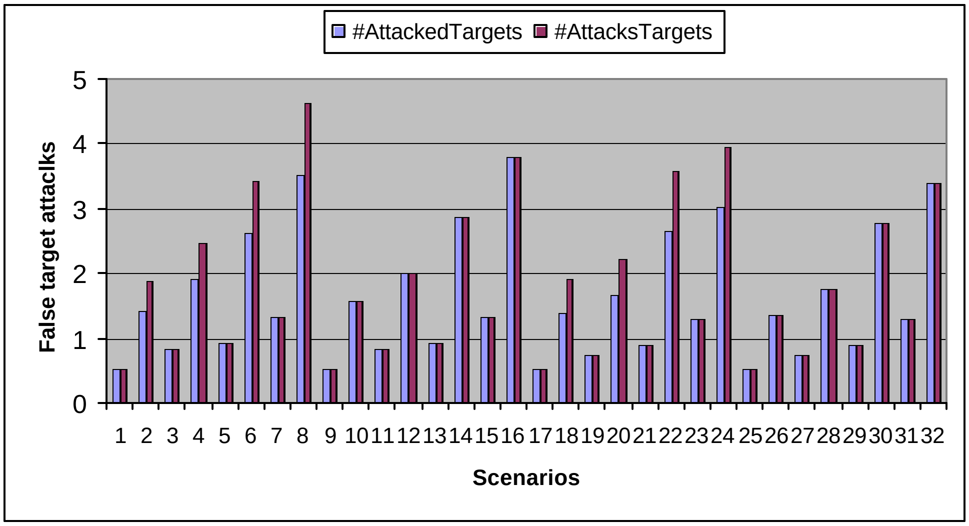

Figure 6 Number of Real Target Attacks for Cooperative Munitions

The number of real targets attacked and the total number of attacks made on real targets by non-cooperative munitions is shown Figure 7.

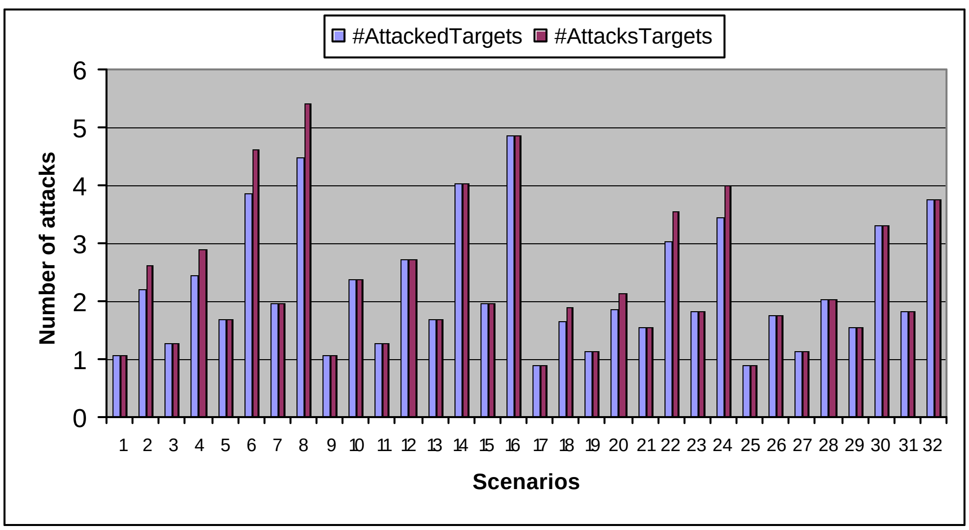

Figure 7 Number of Real Target Attacks for Non-cooperative Munitions

At low search weight and low warhead lethality scenarios ($P_K = 0.5$) cooperative munitions execute more attacks on previously attacked targets than the non cooperative munitions. Again, this is due to the fact that benefit calculations at low warhead lethality gives a higher probability that the attacked target is still alive than the high warhead lethality scenarios. In addition, a low search weight promotes in munitions attacking on known targets rather than looking for additional new targets. As a result cooperative munitions executed multiple attacks on targets that have been attacked previously but likely still alive. For all of the other scenarios munitions did not attack an already attacked target. If munitions had continued the search longer for additional targets rather than attacking previously attacked ones, the number of real target kills might have been higher.

Another factor that shows the performance of munitions is the ratio of real target attacks to the total number of attacks. The ratio of real target attacks to the total number of attacks for cooperative and non-cooperative munitions is shown in Figure 8. The overall ratios for cooperative and non-cooperative munitions are 0.92 and 0.7 respectively. The performance of non-cooperative munitions is significantly worse than the cooperative behavior. For the high FTAR scenarios, the ratio of real target attacks to the total number of attacks for non- cooperative munitions varies from 0.39 to 0.57. Therefore, nearly half of the total attacks executed by non- cooperative munitions have been on the false targets. The cooperative munitions achieved a ratio of 0.8 for the same cases. Even though, as mentioned in previous sections, non cooperative munition killed more targets than the cooperative munitions, they also attacked a great number of false targets.

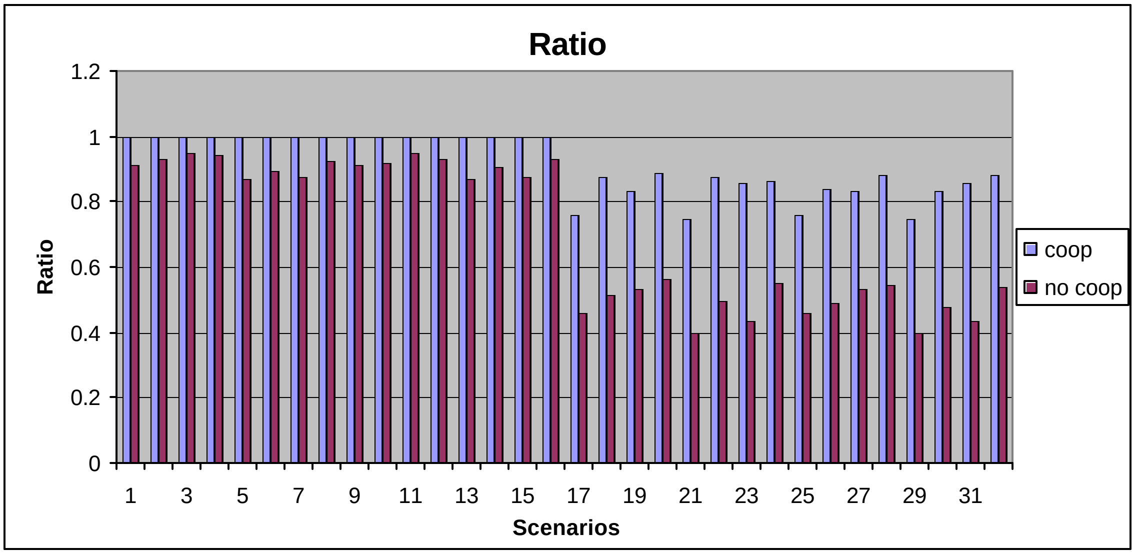

Figure 8 Ratio of Real Target Attacks to Total Number of Attacks

4.8 Hit Formula

A hit formula has been used to evaluate the performance of cooperative and non-cooperative munitions. High and low priority targets were used in this research: two high priority and four low priority targets are distributed among 26 false targets. A hit formula has been calculated in the simulation to see the effects of discrimination between the target priorities and the effects of false target attacks. The hit formula can be expressed as (1):

$$\textit{Hit Formula} = 2.\ (\#\ \textit{High priority attacks}) + (\#\ \textit{Low priority attacks}) - (\#\ \textit{false target attacks}) \qquad (4.1)$$

As can be seen from the formula, emphasis is put on high priority attacks by multiplying it by two and a penalty is given to false target attacks by subtracting it from the overall hit formula value. Figure 9 shows the performance of cooperative and non-cooperative munitions in terms of the hit formula.

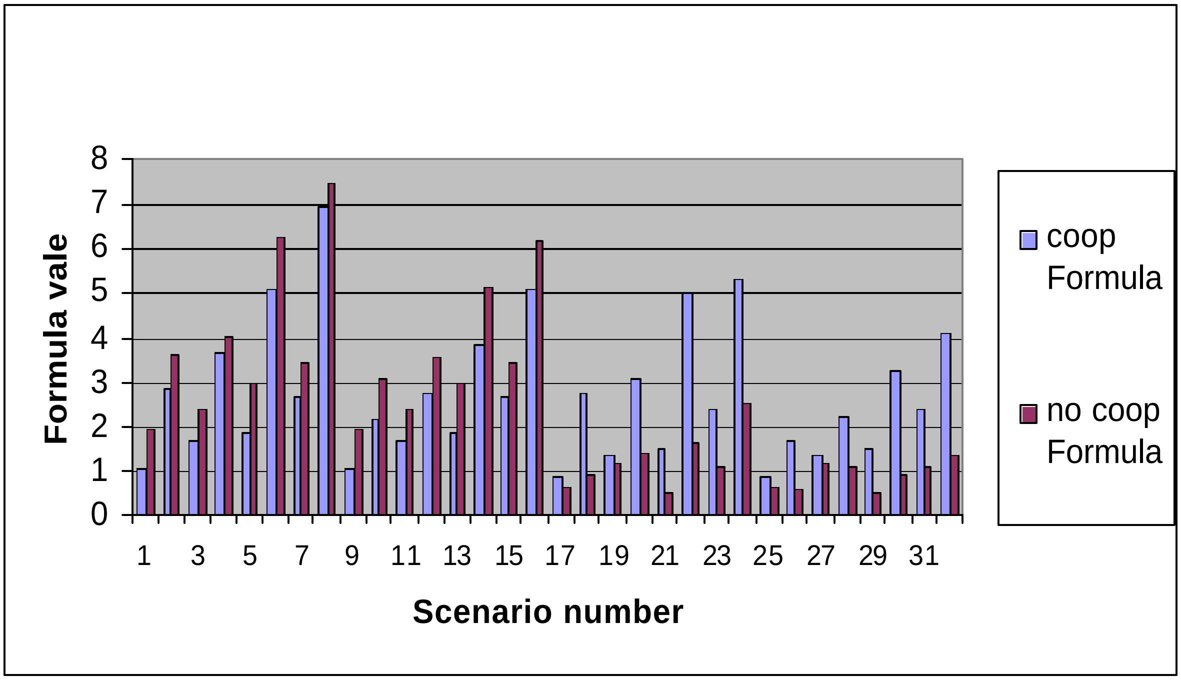

Figure 9 Performance of Cooperative and Non-cooperative Munitions for Hit Formula

Non-cooperative munitions achieved better formula values for the first 16 low FTAR value scenarios, but for high FTAR values (scenarios 17-32) cooperative munitions outperformed the non-cooperative munitions. As discussed in previous sections non-cooperative munitions executed more attacks on false and real targets, but the relatively low number of false target attacks for the low FTAR scenarios allowed the non-cooperative munitions to outperform the cooperative ones in terms of the hit formula. For higher FTAR scenarios, the cooperative munitions were more likely to have munitions still available to attack high priority targets, and more likely to attack high priority targets with more than one munition to achieve target kill.

4.9 Discrimination between Target Types

In this section the ability of cooperative and non-cooperative munitions of discriminating between high and low priority targets will be analyzed. Figure 10 shows the ratio of high priority attacks to total real target attacks for cooperative and non-cooperative munitions for low FTAR value scenarios (see Appendix for parameters).

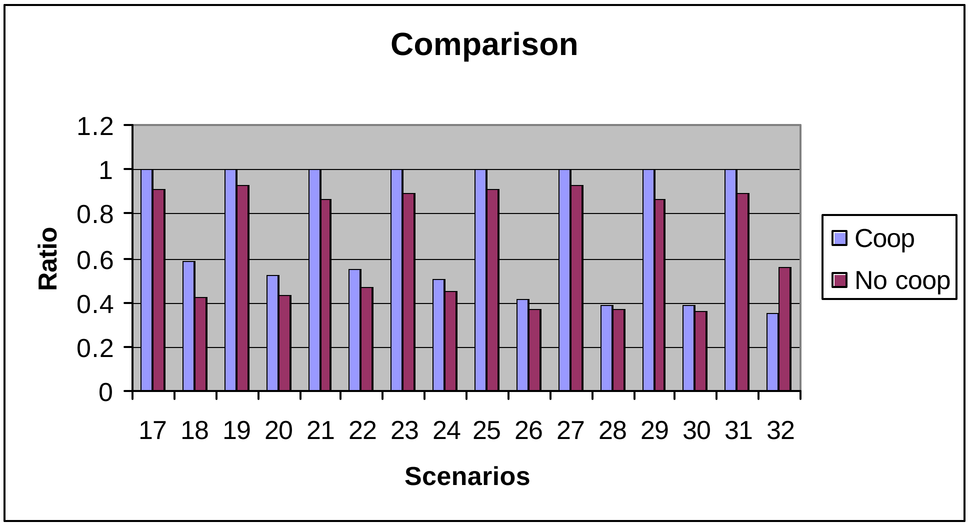

Figure 10 Comparisons of Ratio of High Priority Attacks to Total Real Target Attacks

Although cooperative munitions have executed fewer attacks on targets through the simulation, they improve the quality of attacks. They attack high priority targets at a higher ratio than the non-cooperative munitions. This is an important improvement in favor of cooperative behavior. In real life scenarios it might be very important to distinguish between target priorities to accomplish the mission successfully. It is often more beneficial to destroy the high priority targets rather than destroying greater number of low priority targets.

V. Conclusion and Recommendations

5.1 Conclusions

In this research the performance of cooperative and non-cooperative behavior in autonomous wide area search munitions has been investigated. As discussed in chapter I, scenarios and munitions used in this research are generic and conclusions made on the performance can be applied to a broad family of wide area search munitions.

The results of the simulation were examined under characteristics of warhead lethality, ATR capability, false target attack rate, number of munitions deployed in the simulation, and search weight. Number of killed targets, false target attacks, Hit formula and total attacks have been studied for all of the above characteristics.

Cooperative munitions a demonstrated significant decrease in the number of killed targets. In comparison, cooperative behavior performed very well in terms of false target attacks. Cooperative behavior reduced the number of false target attacks by 87.2%, and in some scenarios cooperative munitions did not execute any false target attacks, hence making more munitions available for attacking valid targets. A decrease in false target attacks is very important and represents a promising improvement for cooperative behavior. The decrease in the number of killed targets for cooperative behavior is due to the loss of additional time for classification of targets, more missed targets due to a requirement for confirming classification prior to attack and executing multiple attacks on high priority targets. Non-cooperative munitions execute nearly as many attacks on false targets as they do on real targets. This reduces the efficiency of a single munition and wastes valuable munitions.

Cooperative behavior increased the quality of attacks executed on targets. Cooperative munitions attacked high priority targets at a ratio higher than the non-cooperative munitions achieved. This shows that cooperative behavior can improve the selectivity of wide area search munitions. However, the effort for cooperative munitions to attack high priority targets may reduce the number of total attacks that can be executed. The cooperative munitions achieved better hit formula values for high FTAR values and for overall results due to the low number of false target attacks and a greater number of high priority target hits.

Although cooperative munitions performed worse than the non-cooperative munitions in terms of target kills, for low warhead lethality, high P_{TR}, greater number of munitions and high FTAR scenarios cooperative behavior achieved better results when compared to its performance for high warhead lethality, low P_{TR}, fewer number of munitions and low FTAR scenarios. FTAR and probability of target report are competing objects. For a given munition system, lower FTAR and higher P_{TR} cannot be achieved simultaneously. One must make some trade off between these competing objects. Keeping FTAR too low leads the ATR system to overlook some alarms and results in higher rate of missed targets. Likewise keeping P_{TR} too high makes the ATR system very sensitive to any kind of alarms detected by the sensor, resulting in a higher FTAR due to the misidentification non-targets.

One suggestion for trade off between these objectives is to adjust the ATR to keep P_{TR} high, and apply cooperative behavior to the munition system to achieve the desired low false target attack rates. This is a cost effective way to get the desired ATR performance without resorting to a larger, more expensive sensor/ATR system. Further, combining this approach with small low cost warheads (low P_K) results in small munitions that can be employed in greater numbers. The platform that launches these wide area search munitions will have the ability to carry more munitions to achieve the mission with success. The increase in the number of munitions will also increase the reliability of the overall munition system. Hence an effective munition system can be achieved cost efficiently. It is believed that tailoring the degree of cooperation to the real life situation may produce desirable results in terms of mission success.

5.2 Recommendations for Further Research

Modeling real life is beyond the scope of this study. In order to achieve the goal of this research some simplifying assumptions needed to be made. These assumptions and simplifications are left as recommendations for further researches.

1. For the purposes of this research all communication between munitions are assumed reliable and on time. There is no communication delay, signal degradation or broadcasting errors. Communication is one of the important factors of determining the performance of wide area search munitions. Communication faults, broadcasting poor and bad information can be a field of interest for further research.
2. In this research all targets and non-targets are modeled as stationary. Mobile targets will challenge cooperative algorithms because of the need for confirming classification and multiple attacks. If the target has moved, the second munition assigned to a target may have spend additional time relocating it. Mobile targets are left as a recommendation for further research as well.

3. In this research 4 and 8 munition are studied. Increasing the number of the munitions is a very complex procedure and is left as a recommendation as well. The effects due to number of munitions are very significant on performance of cooperative and non cooperative munitions. The effect of greater number of munitions will provide further insight.

Appendix A: Test Matrices

Test Matrix for Non-cooperative Scenarios

Scenario	Cooperation	FTAR	P_K	Nmun	P_{TR}	Search Weight
1	No	0.002	0.5	4	0.8	0.42
2	No	0.002	0.5	4	0.8	0.25
3	No	0.002	0.5	4	0.95	0.42
4	No	0.002	0.5	4	0.95	0.25
5	No	0.002	0.5	8	0.8	0.42
6	No	0.002	0.5	8	0.8	0.25
7	No	0.002	0.5	8	0.95	0.42
8	No	0.002	0.5	8	0.95	0.25
9	No	0.002	0.8	4	0.8	0.42
10	No	0.002	0.8	4	0.8	0.25
11	No	0.002	0.8	4	0.95	0.42
12	No	0.002	0.8	4	0.95	0.25
13	No	0.002	0.8	8	0.8	0.42
14	No	0.002	0.8	8	0.8	0.25
15	No	0.002	0.8	8	0.95	0.42
16	No	0.002	0.8	8	0.95	0.25
17	No	0.02	0.5	4	0.8	0.42
18	No	0.02	0.5	4	0.8	0.25
19	No	0.02	0.5	4	0.95	0.42
20	No	0.02	0.5	4	0.95	0.25
21	No	0.02	0.5	8	0.8	0.42
22	No	0.02	0.5	8	0.8	0.25
23	No	0.02	0.5	8	0.95	0.42
24	No	0.02	0.5	8	0.95	0.25
25	No	0.02	0.8	4	0.8	0.42
26	No	0.02	0.8	4	0.8	0.25
27	No	0.02	0.8	4	0.95	0.42
28	No	0.02	0.8	4	0.95	0.25
29	No	0.02	0.8	8	0.8	0.42
30	No	0.02	0.8	8	0.8	0.25
31	No	0.02	0.8	8	0.95	0.42
32	No	0.02	0.8	8	0.95	0.25

Test Matrix for Cooperative Scenarios

Scenario	Cooperation	FTAR	P_K	Nmun	P_{TR}	Search Weight
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6	Yes	0.002	0.5	8	0.8	0.25
7	Yes	0.002	0.5	8	0.95	0.42
8	Yes	0.002	0.5	8	0.95	0.25
9	Yes	0.002	0.8	4	0.8	0.42
10	Yes	0.002	0.8	4	0.8	0.25
11	Yes	0.002	0.8	4	0.95	0.42
12	Yes	0.002	0.8	4	0.95	0.25
13	Yes	0.002	0.8	8	0.8	0.42
14	Yes	0.002	0.8	8	0.8	0.25
15	Yes	0.002	0.8	8	0.95	0.42
16	Yes	0.002	0.8	8	0.95	0.25
17	Yes	0.02	0.5	4	0.8	0.42
18	Yes	0.02	0.5	4	0.8	0.25
19	Yes	0.02	0.5	4	0.95	0.42
20	Yes	0.02	0.5	4	0.95	0.25
21	Yes	0.02	0.5	8	0.8	0.42
22	Yes	0.02	0.5	8	0.8	0.25
23	Yes	0.02	0.5	8	0.95	0.42
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25	Yes	0.02	0.8	4	0.8	0.42
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31	Yes	0.02	0.8	8	0.95	0.42
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14. ABSTRACT

This research investigates the effectiveness of autonomous wide area search munitions using cooperative and non-cooperative behavior algorithms under various scenarios. The scenarios involve multiple autonomous munitions searching for an unknown number of targets with different priorities at unknown locations. For the cooperative cases, communications are allowed between the munitions to help locate, identify, and decide to pursue an attack on a target or to continue searching the rest of the battlefield. For non cooperative cases, munitions independently search, detect, identify and decide to attack an identified target or continue to search. Performance of the cooperative munitions depends on numerous parameters such as target types, number, mobility, battlefield characteristics, warhead lethality, decision objectives, and variability in the battlefield.

The results were examined under characteristics of warhead lethality, ATR capability, false target attack rate, number of munitions deployed in the simulation, and search weight. Cooperative munitions demonstrated significant decrease in the number of killed targets. Cooperative behavior reduced the number of false target attacks significantly.

15. SUBJECT TERMS

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